Light sources

Faster, brighter, shorter

A proposed new facility - LUX – will combine accelerator and laser systems to study ultrafast dynamics across a wide range of science.

Ultrafast X-rays have been identified in numerous workshops and reports world-wide as a key area ripe for new scientific investigations – with femtosecond pulses allowing detailed study of atomic motion during physical, chemical, and biological reactions. Ultrafast lasers covering most of the visible, infrared, and ultraviolet regions of the spectrum already provide the capability to measure bond-breaking in chemical reactions with both high resolution and very short pulses. Thus, experimenters have used lasers to tremendous advantage for thousands of investigations of time dynamics, many of which are absolutely critical to research in solid state physics, semiconductors, photochemistry, and photobiology. However, until now ultrafast time domain studies in the X-ray region have been almost completely lacking, although they are needed to refine the picture of dynamics at the timescales of atomic vibration periods – about 100 fs and less.

Through the use of synchrotron radiation and by the novel conversion of intense laser pulses into soft and hard X-rays, scientists have recently been able to perform for the first time some innovative experiments, such as Bragg diffraction studies of phase transitions, and even attosecond electron redistribution in Auger electron processes. However, the laser-based X-ray fluxes are low, the signal levels weak, and the experiments are challenging to accomplish.

LUX - a Linac-based Ultrafast X-ray/laser facility - is a concept to produce ultrashort X-ray pulses in a highly refined manner for experiments across all areas of the physical, chemical and biological sciences. The facility will provide an increase of X-ray flux by several orders of magnitude, and would be accessible to a large number of users. Ultrafast lasers would be available for "pump-probe" experiments at femtosecond resolutions, where a pulse from a laser excites (pumps) the system under study, while the X-ray pulse is used to probe the system configuration as a snapshot in time after the pump pulse. Figure 1 shows the concept.

While the approximately 40 available light sources in the world are largely limited to static spectroscopies, microscopies, and structures, LUX will be the first to be designed from the start as a user facility for femtosecond X-ray dynamics, with precise timing as an integral requirement. It will offer high repetition rates, tunability, and multiple laser sources for excitation and probe experiments, with pulses one thousand times shorter than typical third-generation light sources.

Although pump-probe experiments represent some of the most important techniques, involving a femtosecond laser as a pump and the ultrafast linac-based X-ray source as the probe, the facility will also be designed to accommodate multidimensional coherent laser spectroscopies, such as three-laser pump beams and an X-ray probe, as well as two X-ray wavelengths for double-resonance X-ray pump and probe spectroscopies. Most of these novel forms of spectroscopies with X-rays have not even been delineated yet.

The LUX proposal is based on a recirculating electron linac, which provides a compact and cost-effective configuration for the production of intense ultrafast extreme ultraviolet (EUV) and X-ray pulses, with tight synchronization to sample excitation lasers. The provision of a broad photon spectrum covering the whole range from EUV to hard X-ray wavelengths allows for both spectroscopy and diffraction studies, probing nuclear positions as well as electronic, chemical or structural properties. The design specification of a 10 kHz pulse repetition rate is matched to pump-probe experiments and allows rapid data acquisition, and sample relaxation or replacement.

The facility is designed to produce ultrafast EUV and soft X-rays by a harmonic-cascade free-electron laser (FEL) technique, while hard X-rays are produced by a novel manipulation of the electron bunches followed by compression of the photon beam. The FEL process is initiated by a "seed" laser, which allows tunability both of wavelength and of pulse duration, from hundreds to tens of femtoseconds. Hard X-ray pulses are produced in superconducting insertion devices - undulators produce narrow-band peaks with harmonics out to 10 keV and higher, and wigglers produce broad-band pulses extending to even shorter wavelengths.

The major components and systems of LUX involve existing accelerator technologies: RF photo-injector guns, superconducting linear accelerators, magnet lattices in the arcs and straight sections, transversely deflecting cavities, harmonic-generation in FELs, narrow-gap short-period undulators, X-ray manipulation in optical beamlines, and a variety of short-pulse laser systems. Figure 2 shows the machine layout. In LUX, high-quality (low emittance, high charge) electron bunches produced in an RF photocathode are accelerated to approximately 100 MeV in an injector linac before being turned into the main linac. The main linac accelerates the electron bunches by about 700 MeV on each pass, resulting in a final energy of approximately 3 GeV after four passes. After acceleration to 3 GeV, the electron bunches pass through insertion devices to produce radiation, supplied to multiple beamlines.

The beam quality requirements of the RF photocathode gun have already been demonstrated, with a normalized emittance of approximately 3 mm-mrad at 1 nC charge. The flexibility of the LUX lattice design allows the control and preservation of the transverse and longitudinal emittances of the electron beam, minimizing the influence of collective effects, and allowing the manipulation of the picosecond electron bunches to produce femtosecond X-ray pulses.

To produce ultrafast hard X-rays, at the exit of the final arc the electron bunches receive a time-correlated vertical kick in a dipole-mode RF cavity – the head is kicked up and the tail down, while the centroid is unperturbed. The electrons then radiate X-rays in the downstream chain of undulators and wiggler magnets, imprinting this head-tail correlation in the geometrical distribution of the X-ray pulse. The correlated X-ray pulse is then compressed by using asymmetrically cut crystal optics to achieve the ultra-short X-ray pulse length.

In addition, high-flux, short-pulse photons will be produced over an energy range of tens of electron volts to a thousand electron volts by a laser-seeded harmonic-cascade FEL. The high-brightness electron beam is extracted from the recirculating linac, and passed through an undulator where a co-propagating seed laser results in a modulation of the charge distribution over a short length of the bunch. This modulation enhances radiation in a following undulator at shorter wavelengths that are harmonically related to the seed. The process is repeated by modulating a fresh portion of the beam this time with the harmonic radiation produced in the previous undulator.

Sophisticated laser systems will be an integral part of the LUX facility, providing experimental excitation pulses and stable timing signals, as well as the electron source through the photocathode laser. Each endstation will have its own dedicated laser system with optical filtering and diagnostics, all contained within a stable and controlled environment. Multiple tunable lasers covering infra-red to ultraviolet wavelengths with a range of pulse durations are required for experiment initiation, together with sophisticated temporal and spatial filtering to optimize performance for specific experimental applications.

Synchronization and timing of the ultra-short X-ray pulses with respect to the experimental excitation pulse is critical in studies of ultra-fast dynamics. For LUX the techniques of optically seeded systems and bunch manipulation prove insensitive to the usual timing jitter arising from electron acceleration in RF systems. A laser master oscillator provides stable optical pulses, and optical distribution systems transport these pulses to each beamline, with feedback based on interferometric measurements to stabilize the path lengths. Conversion to microwave signals by photodiodes allows generation of the RF signals for the accelerator, and for phase-locking of endstation lasers. Lasers may also be optically seeded directly from the master oscillator.

The LUX project is presently in a pre-conceptual design phase, and the facility design is being optimized to meet the demands of the growing number of scientific applications. Combining state-of-the-art accelerator and laser systems to produce a unique X-ray facility for the study of ultrafast dynamics presents exciting challenges and the prospect of a bountiful future in new areas of science.

Further reading:
More information may be found at http://lux.lbl.gov/.

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Figure 1. Schematic of the pump-probe concept. A laser pulse excites or “pumps” the sample into a state that then evolves in time. An ultrafast X-ray pulse arriving at time Δt after the pump pulse then momentarily probes the state of the sample at that time, in this example by causing emission of ions which are then detected.

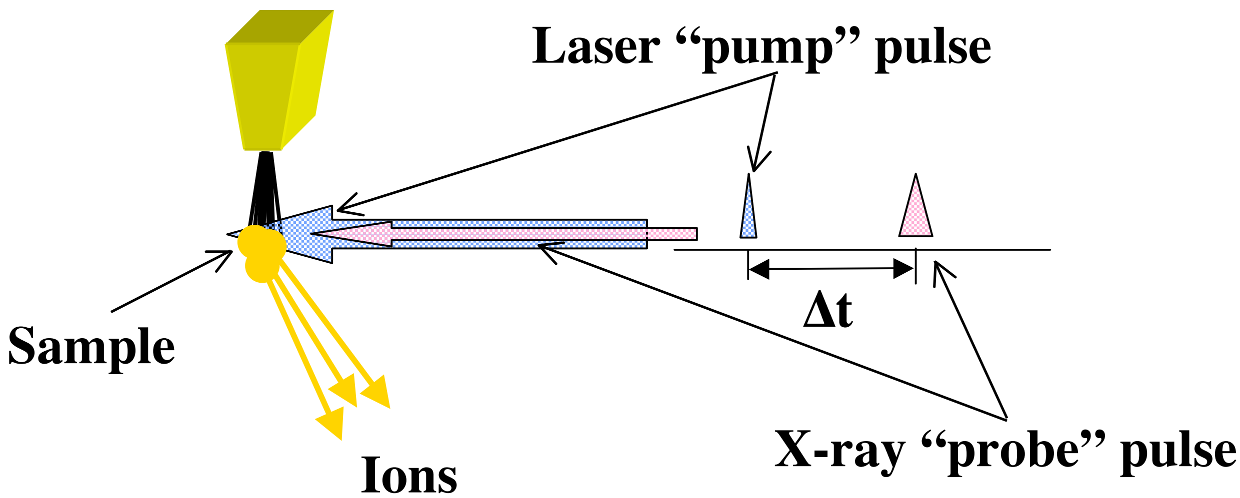

Figure 2. The layout of the LUX machine showing experimental beamlines, harmonic-cascade FEL chains, and major accelerator components. The machine footprint is approximately 150 x 50 m. A capacity of approximately 20 beamlines is shown.